Measurements of optical-heterodyne conversion in low-temperature-grown GaAs

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A low-temperature-grown GaAs interdigitated-electrode photomixer is used to generate coherent power at microwave frequencies. An output power of 200 μW (-7 dBm) is generated by pumping the photomixer with two 70-mW modes of a $Ti{:}Al_2O_3$ laser, separated in frequency by 200 MHz. This represents an optical-to-microwave conversion efficiency of 0.14%, which is within 50% of a prediction based on optical-heterodyne theory. When two lasers are used and the frequency of one is tuned with respect to the other, the output frequency of the photomixer increases smoothly and the output power is nearly constant up to 20 GHz. At higher frequencies the power decays because of parasitic capacitance.

Low-temperature-grown (LTG) GaAs possesses a subpicosecond electron-hole recombination time[1] and a photocarrier mobility ($\mu \approx 200\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$) that is very high for a semiconductor having such a short recombination time. In addition to these remarkable properties, it displays a high breakdown field ($E_B > 4\times 10^5\ \mathrm{V\,cm^{-1}}$). Together, these properties have led to impressive optoelectronic device results such as the generation of a 600-V-peak pulse having a full width at half-maximum of 2 ps (Ref. 2) and the direct detection of intense subpicosecond laser pulses with a responsivity of 0.1 A/W.[3] In this letter we present experimental results for LTG-GaAs as an optical-heterodyne converter, or photomixer.

Photomixing was proposed nearly three decades ago as a means of generating coherent radiation in the microwave region.[4] However, useful levels of output power have not been obtained because of the lack of robust photomixers and high-quality tunable lasers. With recent advances in high-speed III-V optoelectronic devices and solid-state lasers, interest in power generation by photomixing has been revived and new methods have been pursued. For example, a GaAs field-effect-transistor photomixer pumped by tunable dye lasers has generated coherent signals up to 61 GHz.[5] However, the output power generated by optical-heterodyne methods has been limited to the 1-μW level. In this letter, we demonstrate an LTG-GaAs photomixer having an output power of 0.2 mW and a response that is flat out to at least 20 GHz.

The photomixer consists of 10 interdigitated metal electrodes that are defined on the top surface of a LTG-GaAs epitaxial layer. The electrodes were made from gold and fabricated by electron-beam lithography and photoresist lift-off. The electrodes were 1.0-μm wide, 20-μm long, and separated by 1.0-μm-wide gaps. The underlying LTG-GaAs layer was grown by molecular-beam epitaxy on a semi-insulating GaAs substrate at a temperature of 195 °C. The thickness of the layer was approximately 1.0 μm. From previous characterizations on material grown under the same conditions, this LTG-GaAs layer is expected to have a photocarrier lifetime of approximately 0.6 ps and a breakdown electric field of approximately $5\times 10^5\ \mathrm{V\,cm^{-1}}$. To couple power out of the photomixer at microwave frequencies, the electrodes were located in the gap between the center line of a coplanar waveguide and the ground plane, as shown schematically in Fig. 1. The characteristic impedance of the coplanar waveguide was 50 Ω, so that the output signal could be measured directly with a commercial spectrum analyzer. The coplanar waveguide also has the benefit of a very wide operational bandwidth. In the present configuration, the bandwidth is limited primarily by the parasitic gap capacitance, as discussed below.

The photomixer was optically pumped by two different methods using the arrangement shown in Fig. 2. In the first method, the dependence of photomixer output power on laser pump power at a fixed frequency was measured. The output from a single $Ti{:}Al_2O_3$ laser oscillating simultaneously on two adjacent longitudinal modes was coupled into a single-mode optical fiber and focused upon the interdigitated fingers using an output lens on the end of the fiber. The frequency difference between these modes was 200 MHz, and the pump power was nearly equally divided between them. In the second method, the dependence of photomixer response upon frequency was measured. The beams from a standing-wave $Ti{:}Al_2O_3$ laser and a ring $Ti{:}Al_2O_3$ laser at photon energies $h\nu_1$ and $h\nu_2$, respectively, were fiber optically combined and focused upon the interdigitated fingers. Because the fiber-optic combiner is single mode, the mixing efficiency of the two beams is very close to unity. The difference frequency $|\nu_2-\nu_1|$ was varied by tuning the wavelength of the ring laser relative to the 750-nm ($h\nu = 1.65$ eV) wavelength of the standing-wave laser.

Experimental results in the variable-power mode are given in Fig. 3(a). The output power P_ω from the photomixer at 200 MHz is plotted against the bias voltage V_B between adjacent electrodes with the total incident optical pump power, P_o, as a parameter. P_ω increases monotonically with P_o and V_B. The highest measured value of P_ω was -7.0 dBm with $P_o = 140$ mW and $V_B = 40$ V. With $P_0 = 170$ mW, $P_\omega = -8.4$ dBm was measured at $V_B = 36$ V. However, increasing V_B toward 40 V led to the destruction of the device. In this sample V_B was limited to 40 V or less to guard against electrical breakdown. In a separate photomixer sample of the same design, 50 V was safely applied

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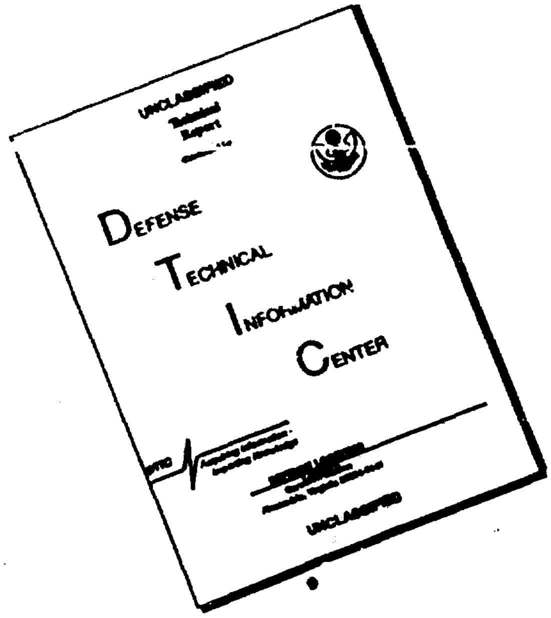

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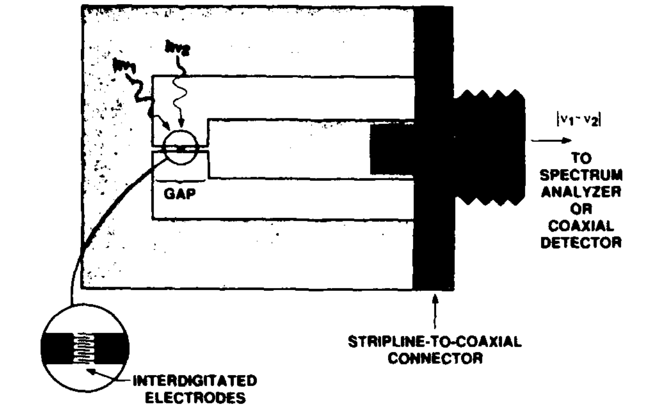

FIG. 1. LTG-GaAs photomixer mounted in coplanar-waveguide structure. The photomixer consists of interdigitated electrodes fabricated in the gap of a coplanar-waveguide transmission line.

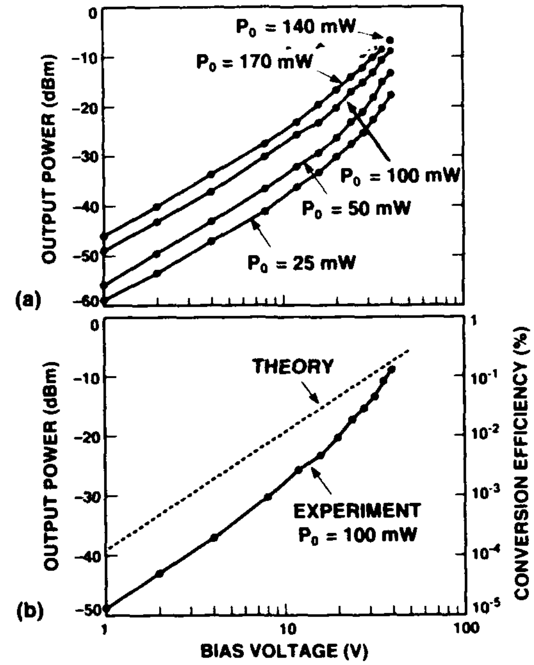

FIG. 3. (a) Output power from photomixer at 200 MHz as a function of bias voltage at five pump powers from the Ti:Al_2O_3 standing-wave laser. (b) Comparison of the experimental results from (a) at $P_o=100$ mW with small-signal photomixer theory.

in the absence of optical power, but the combination of $V_B=50$ V and high P_o led to the destruction of the photomixer.

In Fig. 3(b) we show the optical-to-microwave conversion efficiency ϵ (i.e., the ratio of the output power to the pump power) for $P_o=100$ mW. Both P_ω and ϵ increase almost quadratically for V_B up to about 20 V, and then increase superquadratically at higher voltages. At $V_B=40$ V, $\epsilon=0.14\%$, which is the highest value obtained to date. Also shown in Fig. 3(b) is a theoretical curve based on the following expression for P_ω at a circular difference frequency ω,

$$P_\omega=\frac{\frac{1}{2}(V_B G_0)^2 R_L}{[1+(\omega\tau)^2][1+(\omega R_L C)^2]}. \quad (1)$$

In this expression, G_0 is the time-averaged photoconductance of the photomixer, R_L is the ac load resistance, C is the capacitance of the interdigitated structure, and τ is the photocarrier lifetime. This expression is valid under the small-signal conditions $G_0R_L \ll 1$, which is the case in the present experiments. For example, at $V_B=40$ V and $P_o=100$ mW, we measured a G_0 of approximately 50 μS, resulting in $G_0R_L=0.0025$. The expression in Eq. (1) can be understood by noting that the perfect mixing of two laser lines of equal power generates a photoconductive response consisting of a dc component and a sinusoidal difference-frequency component, both of amplitude G_0.[6] If the photoconductor is connected to the series combination of the bias supply and R_L, the sinusoidal component gives rise to a nearly sinusoidal current through R_L of amplitude V_BG_0 when $G_0R_L \ll 1$. The power delivered to R_L is then approximately $\frac{1}{2}(V_BG_0)^2R_L$. The two terms in the denominator represent a roll off in the power with frequency caused by the finite photocarrier lifetime and the displacement current through the interdigitated-electrode capacitance, which is calculated to be 6.1 fF in this photomixer.[7] At the difference frequencies of the present experiments, $\omega\tau \ll 1$ and $R_LC \ll 1$, so that the two terms in the denominator of Eq. (1) are very close to unity. A more accurate expression for the output power is derived in Ref. 8.

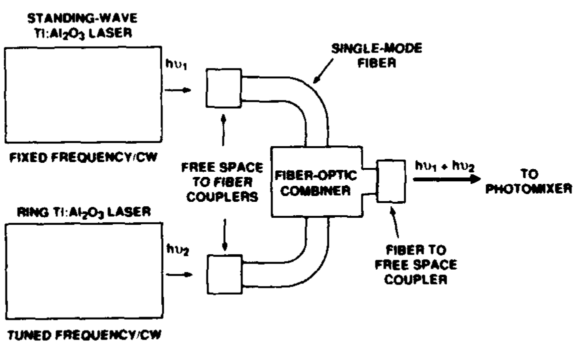

FIG. 2. Optical arrangement used to pump the LTG-GaAs photomixer. The Ti:Al_2O_3 standing-wave laser operates on two adjacent longitudinal modes, and the Ti:Al_2O_3 ring laser operates on a single mode whose wavelength is fine tuned by an internal etalon. The center wavelength of both lasers is approximately 750 nm.

In Fig. 4 we plot the experimental output power as a function of P_o for $V_B=8$ and 36 V, and we superimpose on this plot loci of constant ϵ. At $V_B=36$ V, ϵ increases from 0.040% to 0.085% as P_o increases from 25 to 170 mW. A more rapid increase is expected from Eq. (1) since in the small-signal limit G_0 should increase linearly with P_o as given by $G_0=SP_o/V_B$, where S is the external responsivity. Using the experimental value of $S=0.026$ A/W measured at $V_B=36$ V and low pump power, we obtain the theoretical output power shown in Fig. 4. At the lowest P_o the experiment and theory are in excellent agreement, but at higher pump powers the experiment deviates on the low side. Also shown in Fig. 4 is the theoretical P_ω for $V_B=8$ V calculated using the experimental value $S=0.0025$ A/W. In this case the theory exceeds the experiment by over 7 dB at the lowest P_o and the discrepancy grows with

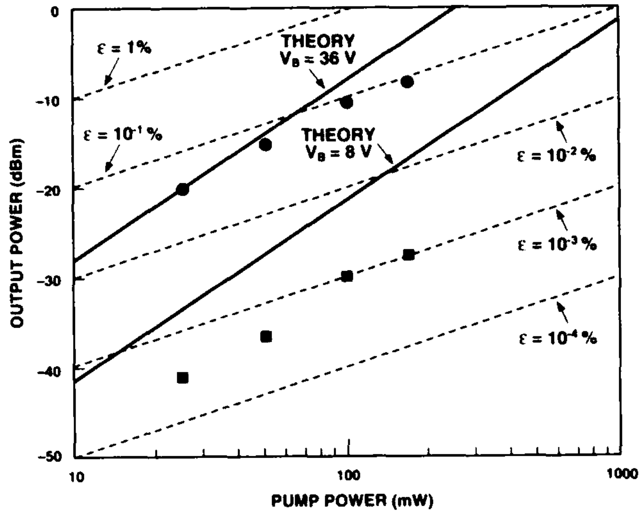

FIG. 4. Output power from photomixer at 200 MHz as a function of pump power at two bias voltages, 8 (squares) and 36 V (circles). Also shown are curves (solid lines) of the theoretical output power for these bias voltages and loci (dashed lines) of constant conversion efficiency.

increasing pump power. Inspection of Fig. 3(b) shows that this discrepancy occurred over the entire range of bias except at the high end. The reason for this trend is not presently understood.

We suspect that the subquadratic dependence of experimental output power on pump power at $V_B=36$ V is a result of device heating. A crude estimate of the temperature at the surface of the photomixer is obtained by assuming that the GaAs substrate is semi-infinite and that all of the optical pump power is absorbed in an infinitesimal thickness just below the photomixer surface. This leads to a temperature rise at the surface of $\Delta T \approx (P_a+P_{dc})/2\kappa D$,[9] where P_a is the optical power absorbed in the photomixer, P_{dc} is the dc electrical power dissipation, κ is the room-temperature thermal conductivity of GaAs (0.46 W cm^{-1} K^{-1}), and D is the width of the active area of the photomixer (assumed to be square). The operating temperature is thus $T_{op}=T_0+\Delta T$, where T_0 is the ambient temperature. From considerations of geometric optics, P_a is given by $P_a=tP_0w_g/(w_g+w_e)$, where t is the optical transmissivity through the air-GaAs interface, w_e is the width of the electrodes, and w_g is the width of the gaps. At our optical wavelength of 750 nm, $t\approx 0.67$,[10] so that $P_a \approx 0.33P_o$. At a bias voltage of 36 V, the values of P_{dc} are approximately 27, 41, 72, and 104 mW for $P_o=25$, 50, 100, and 170 mW. Thus for $T_0=25$ °C, the approximate values of T_{op} are 44, 56, 82, and 112 °C at the respective pump powers.

The dependence of photomixer output power on difference frequency was measured with $P_o=25$ mW and $V_B=36$ V. Back reflection into the ring laser at higher pump powers caused the laser to run multimode and thus precluded accurate measurements. The output power was measured up to 50 GHz with a coaxial diode detector. The output power was practically constant with frequency up to 20 GHz and then rolled off at approximately 6 dB/octave. We attribute this roll off to the parasitic effect of the displacement current through the capacitance of the coplanar-waveguide gap shown in Fig. 1. From the dimensions of the coplanar gap (0.6-mm wide by 0.3-mm long), we estimate its capacitance as 90 fF. Combined with the 50-Ω load, the gap capacitance leads to a 3-dB roll off frequency of 35 GHz in agreement with the experiment. The intrinsic photocarrier lifetime and interdigitated-electrode capacitance are expected to yield 3-dB roll off frequencies of 265 and 522 GHz, respectively. By reducing the width of the center conductor of the coplanar waveguide, we expect that improved photomixer packages will have greatly reduced gap capacitance and will provide nearly constant P_ω up to at least 50 GHz.

In summary, we have demonstrated a LTG-GaAs interdigitated structure operating as an optical-heterodyne converter, or photomixer. The highest experimental output power was 200 μW at a frequency of 200 MHz, and the conversion efficiency at this output power was 0.14%. The frequency response of the photomixer was limited to about 25 GHz by parasitic capacitance, but the experimental results are consistent with a much higher intrinsic bandwidth.

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[1] J. F. Whitaker, J. A. Valdmanis, M. Y. Frankel, S. Gupta, J. M. Chwalek, and G. A. Mourou, Microelectron. Eng. **12**, 369 (1990).
[2] M. Y. Frankel, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, IEEE Trans. Electron. Devices **ED-37**, 2493 (1990).
[3] Y. Chen, S. Williamson, T. Brock, F. W. Smith, and A. R. Calawa, Appl. Phys. Lett. **59**, 1984 (1991).
[4] R. H. Pantell, M. DiDomenico, Jr., O. Svelto, and J. N. Weaver, *Proceedings of the Third International Conference on Quantum Electronics*, edited by P. Grivet and N. Bloembergen (Columbia University Press, New York, 1964), Vol. 2, p. 1811.
[5] D. V. Plant, D. C. Scott, D. C. Ni, and H. R. Fetterman, IEEE Microwave Guided Wave Lett. **1**, 132 (1991).
[6] R. H. Kingston, *Detection of Optical and Infrared Radiation* (Springer, Berlin, 1978).
[7] J. B. D. Soole and H. Schumacher, IEEE Trans. Electron Devices **ED-37**, 2285 (1990).
[8] E. R. Brown, F. W. Smith, and K. A. McIntosh, J. Appl. Phys. **73**, 1480 (1993).
[9] R. A. Murphy (private correspondence).
[10] J. S. Blakemore, J. Appl. Phys. **53**, R123 (1982).

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